Accreting neutron star spins and the equation of state

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Abstract. X-ray timing of neutron stars in low-mass X-ray binaries (LMXBs) with the *Rossi X-ray Timing Explorer* has since 1996 revealed several distinct high-frequency phenomena. Among these are oscillations during thermonuclear (type-I) bursts, which (in addition to persistent X-ray pulsations) are thought to trace the neutron star spin. The recent discoveries of 294 Hz burst oscillations in IGR J17191−2821, and 182 Hz pulsations in Swift J1756.9−2508, brings the total number of measured LMXB spin rates to 22. An open question is why the majority of the ≈ 100 known neutron stars in LMXBs show neither pulsations nor burst oscillations.

Recent observations suggest that persistent pulsations may be more common than previously thought, although detectable intermittently, and in some cases at very low duty cycles. For example, the 377.3 Hz pulsations in HETE J1900.1−2455 were only present in the first few months of it's outburst, and have been absent since (although X-ray activity continues). Intermittent (persistent) pulsations have since been detected in a further two sources. In two of these three systems the pulsations appear to be related to the thermonuclear burst activity, but in the third (Aql X-1) they are not. This phenomenon offers new opportunities for spin measurements in known systems.

Such measurements can constrain the poorly-known neutron star equation of state, and neutron stars in LMXBs offer observational advantages over rotation-powered pulsars which make the detection of more rapidly-spinning examples more likely. Even so, spin rates of at least 50% faster than the present maximum appear necessary to give constraints stringent enough to discriminate between the various models. Although the future prospects for such rapidly-spinning objects do not appear optimistic, several additional observational approaches are possible for LMXBs. The recent study of EXO 0748−676 is an example.

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INTRODUCTION

The equation of state (EOS) of cold matter at super-nuclear densities remains one of the foremost outstanding problems for fundamental physics (e.g. [1]). The major uncertainty in high-density quantum chromodynamics theory (which has otherwise been so successful in explaining the properties and behaviour of subatomic particles) is in the regime where the density is at or above that reached in the atomic nucleus. Cold matter beyond nuclear density may be composed primarily of neutrons, as is normally thought, or it could be dominated by exotic components such as hyperons, pion or kaon condensates, or quark matter (e.g. [2]). Such states of matter are *purely theoretical* at the present time, and their detection — whether it be via accelerator experiments, or in the astrophysical "laboratories" available to astronomers — would represent a significant step forward for modern physics.

Particle accelerators probe the conditions in matter at extreme temperatures and densities (up to a factor of ten higher than nuclear). Matter within neutron stars is also expected to reach super-nuclear densities, but at comparatively "cool" temperatures (no more than 10^9 K!). Neutron stars thus play an important complementary role for studies of condensed matter, and measurements which may constrain the EOS are a high priority for observers.

Since the EOS affects the bulk properties (mass and radius) of neutron stars, simultaneous measurement of these parameters with moderate precision in an individual object would in some cases be sufficient to identify the EOS. However, such measurements have proved surprisingly elusive. The masses of neutron stars in binary (rotation-powered) pulsars can be measured in some cases to a fraction of a percent (e.g. [3]) although simultaneous radius measurements are generally not available. While the maximum neutron star mass also provides a constraint on the EOS, most of the measured masses cluster around $1.4 M_\odot$, which is not useful in distinguishing between different models.

Measurement of the spin rate in rapidly-rotating neutron stars provides a relatively model-independent way to constrain the EOS. The maximum spin rate of a neutron star (above which it will break up due to centrifugal forces) can be expressed in terms of the neutron star mass M and radius R, roughly independent of the EOS [1]:

$$\nu_{\rm max} = 1045 (M/M_\odot)^{1/2} (10\,{\rm km}/R)^{3/2}\ {\rm Hz} \qquad (1)$$

where M and R are the neutron star mass and radius. Constraining the possible candidates for the neutron star EOS thus requires detection of ever-more rapidly spinning

neutron stars. The fastest-spinning neutron star presently known is the radio pulsar PSR J1748−2446ad, at 716 Hz [4]. Although it's mass is unknown, assuming a value consistent with the measurements from other radio pulsars leads to an upper radius limit of 14.4 km. Without a mass measurement, this limit does not yet allow us to reject any individual EOS.

A compelling observational goal, then, is to detect ever-more rapidly spinning neutron stars. Despite much effort, progress in this regard has been slow; the detection of PSR J1748−2446ad represented the first increase in the known maximum neutron-star spin rate in 23 years. In the radio band, selection effects make more rapidly-spinning rotation powered pulsars significantly harder to detect. Although these selection effects do not affect spin measurements via X-ray observations of accretion-powered neutron stars, faster-spinning systems have not yet been convincingly detected, suggesting perhaps that some physical mechanism prevents further spin-up.

Regardless, measurement of neutron-star spins in LMXBs remains a high observational priority. In this paper I will discuss the phenomenology of the various types of high-frequency timing phenomena detected to date, and assess the prospects for future detections which may provide the first strong constraints on the neutron-star equation of state.

MEASUREMENT OF NS SPINS IN LMXBS

Evidence of rapid spins in neutron-star LMXBs has been obtained exclusively via observations with the Proportional Counter Array (PCA; [5]) aboard the *Rossi X-ray Timing Explorer* (*RXTE*). The PCA is the only instrument to date with the sensitivity (effective area $\approx$ 6500 cm^2) and time resolution ($\approx 1\ \mu$s) necessary to detect rapid variability from these systems. With the exception of a few high-field neutron stars in LMXB systems (including Her X-1 and GX 1+4), measured spin frequencies fall in the range 45–620 Hz (Table 1), with all but one $>$ 180 Hz. These rapid spins confirm the LMXBs as the evolutionary precursor to the "recycled" millisecond radio pulsars [6, 7].

The LMXBs for which spins have been measured represent only about 20% of the known population of more than 100 (e.g. [8]). It remains an open question as to why it is so difficult to measure the spin in the majority of neutron stars in LMXBs. The two conventional explanations are that either the non-pulsing neutron stars in LMXBs have magnetic fields that are too weak to channel accretion onto polar hotspots (perhaps due to suppression by the accreted material; e.g. [9]) or that the pulsations are scattered by a surrounding region of high optical depth (e.g. [10]). A comparison of the spectral properties of the pulsing and non-pulsing LMXBs does not support the latter explanation ([11, 12], although see also [13]). Furthermore, while the sources which exhibit pulsations tend to have low time-averaged X-ray fluxes (and hence accretion rates), this condition is not sufficient for pulsations to be detectable. The contrast with the rotation-powered pulsars is even more marked when one considers that even the LMXBs which *do* exhibit pulsations, do not exhibit pulsations at all times. Pulsations may only be detected from the accretion-powered millisecond pulsars (AMSPs) when in outburst; similarly, burst oscillations are only detected for a few seconds at the peak of some thermonuclear bursts. This property presents an observational challenge to the measurement of rapid neutron star spins which is quite distinct from the difficulties encountered in searches for rapidly-spinning rotation-powered pulsars.

In further contrast to the rotation-powered pulsars, the spin rate for neutron stars in LMXBs may be measured in two distinct ways[1]: burst oscillations and persistent pulsations. In addition, intermittent (persistent) pulsations have been detected recently in three systems. Below I describe each of these phenomena in more detail.

Burst oscillations

The presence of X-ray bursts are practically a defining characteristic of LMXBs (e.g. [15, 16]). Thermonuclear (type-I) bursts are caused by unstable ignition of accumulated H/He on the surface of accreting neutron stars; the X-ray intensity increases by an order of magnitude within at most a few seconds, before decreasing back to the persistent level within 10–100 s. Although there are several observational aspects which continue to defy explanation (e.g. [17]), the physics of the nuclear ignition and burning are reasonably well understood, and in some cases are fully consistent with observations [18].

Rapid (363 Hz) oscillations were first discovered in bursts from the well-known persistent X-ray source 4U 1728−34 [19]. A power-density spectrum covering the maximum of the burst exhibited multiple closely-spaced peaks, that were later resolved into a continuous upwards frequency drift over the span of the oscillation. Frequency drifts of a few Hz, as well as $\approx$ 10% amplitudes and sinusoidal pulse profiles, subsequently proved to be typical of such oscillations. The high coherence of these oscillations long recommended them as tracers

[1] Here I exclude measurement of the separation frequency of pairs of high-frequency quasi-periodic oscillations, which has long been thought to be approximately equal to or half the spin frequency (although see [14]).

of the neutron star spin, and this conjecture was all but confirmed with the detection of burst oscillations at the persistent pulsation frequency in two accretion-powered pulsars [20, 21].

Burst oscillations have been discovered to date in 14 sources (e.g. [16]; Table 1), at frequencies in the range 45–620 Hz. The oscillations with the lowest frequency were detected by summing power-density spectra of 38 bursts detected from EXO 0748$-$676 [22]. In this source, the oscillations are uniquely not detectable in individual bursts. The highest frequency oscillations to date are from 4U 1608$-$52, at 620 Hz (Hartman et al., 2008, in preparation). The most recent discovery has been in the rapid transient IGR J17191$-$2821. A thermonuclear burst was detected from this system by *RXTE*/PCA on 2007 May 4, in which high-frequency oscillations were present, increasing in frequency from 292 to 294 Hz [23]. As with the other burst oscillation sources, the highest freqency detected is assumed to be the neutron star spin frequency.

Both the average and maximum spin frequencies of the burst oscillation sources are higher than those of the sources with persistent pulsations, so that this phenomenon perhaps offers the best opportunity for increasing the maximum spin rate for rapidly-rotating neutron stars. Evidence for a burst oscillation at > 1000 Hz has already been reported, although the low significance of the signal means that it must be considered a candidate, at best. A peak at 1122 Hz was detected in the power-density spectrum of a 4-s interval late in the tail of a thermonuclear burst from the LMXB transient XTE J1739$-$285 [24]. However, no comparable power excess was detected at this frequency in other (non-overlapping) intervals during the burst, nor in any of the other six bursts observed by *RXTE*. Furthermore, while the significance of the signal was estimated at 3.97σ based on Monte-Carlo simulations, a standard calculation taking into account the total number of trials (for overlapping 4-s time windows up to the Nyquist frequency) suggests the significance is at most 3.5σ. At this relatively low significance, without corroborating detections in other bursts from this source (or at least in other independent, non-overlapping time intervals) this detection cannot yet be interpreted as a spin measurement.

Persistent X-ray pulsations

The accretion-powered millisecond pulsars (AMSPs) have emerged as a distinct class of LMXBs, beginning with the discovery of pulsations in SAX J1808.4$-$3658 in 1998 [25, 26]. Since then, seven more AMSPs (including HETE J1900.1$-$2455, which is more accurately classified as an intermittent pulsar, below) were discovered during transient outbursts typically lasting a few weeks (see [27] for a review). Extensive observations with *RXTE* and other instruments have revealed a number of properties largely characteristic of the class. The outbursts tend to be of short duration, typically a few weeks (but as long as 50 d in XTE J1814$-$338). Pulsations are persistently detected at fractional amplitudes of typically $\sim 5\%$ rms. Where thermonuclear bursts are present, oscillations at the pulsation frequency and roughly the same fractional amplitude are present throughout (e.g. [20, 21]).

The most recently-discovered source, Swift J1756.9$-$2508, is an exemplar of the class. This system was discovered when it began a transient outburst and was detected by the Burst Alert Telescope (BAT) aboard the *Swift* satellite on 2007 June 7 [28]. A subsequent *RXTE* observation of the field showed a significant excess in the power-density spectrum at 182 Hz, confirming the source as an accretion-powered millisecond pulsar. Pulse timing of subsequent observations precisely measured Doppler delays from a 54.7 min binary orbit. The Roche lobe in such an "ultracompact" binary cannot accommodate a main-sequence donor, and the likely companion is He-dominated, with a mass in the range $(6.7\text{–}22) \times 10^{-3}\ M_\odot$. Approximately 13 days later the X-ray flux had dropped to several orders of magnitude below the outburst maximum, and the system had all but returned to quiescence. Searches for X-ray emission from the source over the preceding 2.5 yr for which BAT data was available, as well as the 11.4 yr interval spanned by *RXTE*/PCA and ASM measurements, were unsuccessful (although the sensitivity to faint outbursts is reduced due to the nearby bright source GX 5-1). This suggests that the outburst recurrence time for Swift J1756.9$-$2508 is $\gtrsim 10$ yr, similar to the other ultracompact AMSPs.

The characteristic short-duration outbursts coupled with recurrence times of years result in low time-averaged accretion rates for the AMSPs, of order $10^{-11}\ M_\odot\,\mathrm{yr}^{-1}$ [29]. Five of the eight known systems have been detected only once in outburst, so that the actual recurrence time is unknown. The three systems which have exhibited multiple outbursts, exhibit two distinct recurrence patterns. First, in XTE J1751$-$305, a strong (maximum 50 mCrab) outburst (which led to the source discovery) in 2002 was followed by two much shorter and weaker (≈ 20 mCrab) outbursts, 3 and 2 years later [30, 31]. The estimated fluence from the latest mini-outburst, in 2007, allows a rough measure of the time-averaged flux of $1.6 \times 10^{-12}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, at least an order of magnitude smaller than that of the other AMSPs (excluding possibly Swift J1756.9$-$2508).

The second characteristic pattern of outbursts is typified by the behaviour of SAX J1808.4$-$3658. To date, five outbursts with comparable durations, peak intensi-

ties, and fluences have been observed, that were separated by 2.2 ± 0.6 yr on average [29] The similarity of the outburst profiles extends to large-amplitude variations in X-ray flux for ≈ 15 d prior to the transition to quiescence (see e.g. [32]), as well as the pattern of X-ray pulse variation [33]. For IGR J00291+5934, the system which is most similar in its system properties to SAX J1808.4−3658, a retroactive search of the ASM intensity history revealed evidence for two previous outbursts, 3 and 6 yr earlier. The variability in the outburst intervals for IGR J00291+5934 was substantially less, although a fluence measurement was possible only for the latest outburst, so that the degree of variation of the long-term accretion rate from interval to interval is unknown.

In an earlier study the outburst fluences for SAX J1808.4−3658 were found to be roughly similar, although the fluence measurement for the 2005 June outburst was based on ASM data only, since no public PCA data were available [29]. The now-public PCA observations, which offer excellent coverage of the outburst (even including the rise) allow a much more precise measure of the fluence, of $(4.54 \pm 0.08) \times 10^{-3}\ \mathrm{erg\,cm^{-2}}$. With this more precise measure, I find that the outburst fluences deviate from a constant value at the 5σ level. These variations in the outburst fluence, coupled with the significant variations in the outburst interval, have the consequence that the mean accretion rate in SAX J1808.4−3658 has decreased by about 40% between 1996-1998 and 2002-2005. The mean flux (and accretion rate) plotted for each outburst clearly show a steadily decreasing trend (Figure 1).

The reliability of predictions for subsequent outbursts in these repeating transients is an important factor for observers, not only in the X-ray band. In 2004 December, following an analysis of the recurrence times of the outbursts of SAX J1808.4−3658 and IGR J00291+5934 observed until then, I compared predictions of linear and quadratic fits of the outburst recurrence time. The quadratic fit to the outburst times for SAX J1808.4−3658 resulted in much smaller residuals, and predicted the next outburst in 2005 September–October. The outburst actually occured three months earlier, in 2005 June, an error of just 12% of the recurrence time. The early occurrence of this outburst compared to the prediction may have been related to the fact that the outburst fluence was the smallest yet measured for SAX J1808.4−3658 [29]. Encouraged by the success of the phenomenological model fits in predicting the 2005 June outburst, I make further predictions for the next outbursts in both SAX J1808.4−3658 and IGR J00291+5934. For IGR J00291+5934, the projections of the linear and quadratic fits do not diverge substantially through the time of the next outburst (Fig. 2). The time range spanned by the two models are MJD 54390–54680, i.e. between 2007 October and 2008 July. For SAX J1808.4−3658,

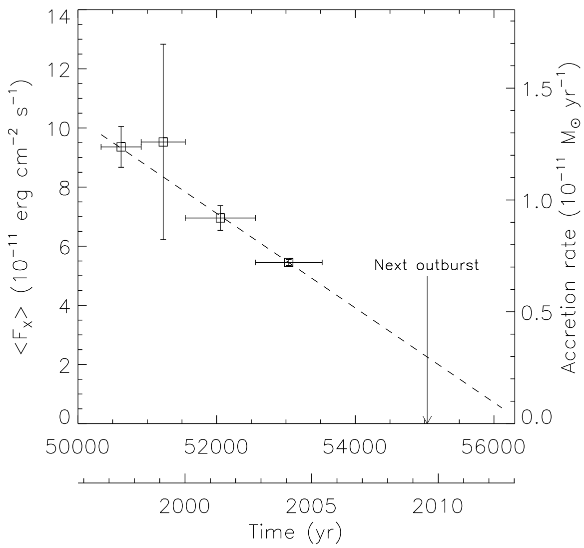

FIGURE 1. Evolution of the long-term time-averaged flux in SAX J1808.4−3658. Each measurement is based on the interval between outbursts and the fluence measured for the outburst which followed, as calculated by [29] but using an improved measure of the outburst fluence for the 2005 June outburst (see text). The right-hand y-axis indicates the corresponding mass accretion rate for a 1.4 $M_\odot$ neutron star with $R = 10$ km at 3.6 kpc. The dashed line is a linear line of best fit, projected through the implied time for the next outburst.

the divergence between the linear and quadratic models is more significant, and in fact the linear model predicts the time for the next outburst as early as 2007 March[2]. Thus, I predict the next outburst to occur sometime between 2007 September and 2008 July.

An alternative prediction for the next outburst in SAX J1808.4−3658 may be made based on the trend of the long-term time-averaged flux. Extrapolating a linear fit to the measurements suggests that sufficient material will have been accreted to the disk to power an outburst of fluence equal to that of 2005 June by MJD 55040 (2009 July; Fig. 1). Thus, an outburst of fluence less than or equal to that in 2005 June will likely occur no later than 2009 July. Interestingly, extrapolating the linear trend further suggests that accretion will cease altogether by around 2013, although this seems implausible!

The wide-field instruments onboard *INTEGRAL*, *Swift* and (to a lesser extent) *RXTE* and *HETE-II* have resulted in a discovery rate for these systems of about 1.4 yr^{-1} since 2002. That this level of coverage has been sus-

[2] Since the X-ray observational coverage of the Galactic bulge region (which includes SAX J1808.4−3658) is better than anywhere else in the sky, we can confidently rule out the sixth outburst having already occurred

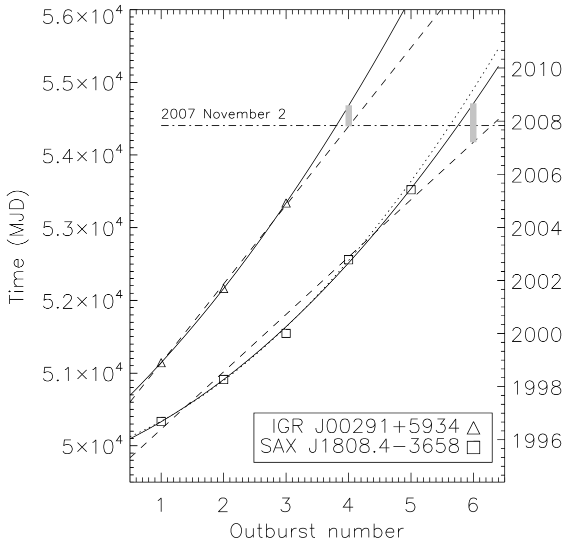

FIGURE 2. Outburst times and phenomenological model fits for the recurrent transients SAX J1808.4−3658 and IGR J00291+5934. The open symbols show the actual start of each outburst detected by *BeppoSAX*, the *RXTE*/ASM or PCA. Linear (*dashed lines*) and quadratic (*continuous lines*) fits to the recurrence times for each source are shown. For SAX J1808.4−3658, I also show the quadratic fit derived prior to the 2005 June outburst (*dotted line*), which was accurate in predicting the time of that occurrence to within 12% (of the outburst interval). The predicted time ranges for the next outburst in each source, calculated as the span of the linear and quadratic models, is shown as the filled grey box.

tained now for 5 yr suggests that the sample of short ($\approx$ 2–3 yr) recurrence time transient AMSPs is practically complete. If this is indeed the case, the future discoveries are likely to be systems with substantially longer recurrence times (such that they have not yet been in outburst since 2002, or even earlier). There are already indications that the discovery rate for AMSPs is decreasing with time. Swift J1756.9−2508, discovered in 2007 June, was the first transient AMSP discovered in 2.5 yr. The new sources discovered in the future, as well as observations of repeat outbursts of the known systems, will be critical to constrain the presently highly uncertain distribution of recurrence times (and hence accretion rates) of these systems.

Intermittent pulsations

Perhaps no less puzzling than the question of why persistent pulsations were only detected in the handful of AMSPs prior to 2006, was the fact that the division between the two classes of systems — the AMSPs and the non-pulsing LMXBs — was so sharp. Despite deep searches by a number of observers, persistent pulsations had not been detected in any other LMXBs, even when a measured burst oscillation frequency could be used to guide the search. Conversely, the pulsations in the first six AMSPs discovered were always present when the sources were detectable with *RXTE*/PCA. This division has since been weakened by the detection of intermittent (persistent) pulsations, first in the long-duration transient HETE J1900.1−2455, and subsequently in two additional sources.

HETE J1900.1−2455 was discovered when a bright thermonuclear (type-I) burst was detected with the *HETE-II* satellite on 2005 June 14, and a subsequent *RXTE*/PCA observation revealed the presence of 377 Hz pulsations [34]. Pulse timing of the observations which followed revealed Doppler shifts from an 83.3 min binary orbit, with a companion likely having mass in the range $(16–70) \times 10^{-3}\ M_{\odot}$. This system soon revealed several properties distinct from the population of AMSPs known until that time. First, the system remained active long after the usual outburst duration for the AMSPs, and in fact is still active (as of 2007 November) at approximately the same mean X-ray flux since 2005 June. Second, the pulse amplitude was unusually low (at most 3% rms), and decreased on a 10-d timescale following several thermonuclear bursts observed early in the outburst [35]. Third, and perhaps most interestingly, was that the pulsations became undetectable on several occasions in the first few months of the outburst, and since 2005 August 20 have not been detected at all. Weekly *RXTE* observations continue with the goal of detecting any change in the system flux or the return of pulsations.

The behaviour of pulsations in this system is enigmatic, having a complex relationship with the presence of thermonuclear bursts. On three occasions the pulsations appeared strongly close to the times of thermonuclear bursts, and then decreasing gradually in amplitude until the next. While this suggests that the bursts themselves triggered the appearance of the pulsations, and in one case a burst preceded the first detection in that observation, in another case the detection of pulsations instead preceded a burst by 2.4 hr. Furthermore, while the source continued bursting after 2005 August 20, the subsequent bursts were not accompanied by pulsations at any level.

The phenomenology has become even more complex with the detection of persistent pulsations in two more systems. Timing analysis of the entire 1.3 Ms of *RXTE*/PCA data accumulated on the well-known transient LMXB Aql X-1 resulted in a single detection of persistent pulsations on 1998 March 10, lasting approximately 150 s [36]. The pulsation, at a frequency of 550.27 Hz, was $\approx$ 0.53 Hz higher than the asymptotic frequency of burst oscillations observed from the source. No bursts were observed within several days of the observation that exhibited pulsations, and no spectral varia-

tion was detected while the pulsations were present. The estimated duty cycle for the pulsation was just 3×10^{-4}. In the globular cluster LMXB SAX J1748.9−2021, pulsations at 442 Hz were detected on several occasions in 2001 and 2005 [37, 38][3]. The oscillations were present during an interval in which several bursts were detected, and exhibited Doppler variations in frequency consistent with a binary orbit with period 8.76 hr.

It may appear an artifical distinction to separate the intermittent pulsars from the seven other "classical" AMSPs, but there are several other distinguishing characteristics. Most notably, the properties of the pulsations in two of the three intermittent systems appear to be related to the occurrence of thermonuclear bursts. Bursts have also been observed from SAX J1808.4−3658 and XTE J1814−338, although with no apparent effect on the persistent pulsations. While it seems implausible that a separate pulse emission mechanism is involved, the mechanism behind the appearance and disappearance of pulsations in these systems is presently a mystery. More detailed studies of the pulse and spectral properties in the known sources, as well as observations of additional examples, may provide the solution.

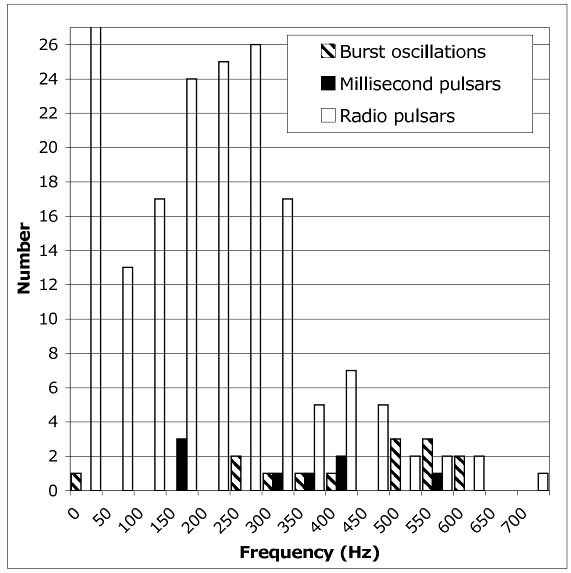

FIGURE 3. The neutron star spin frequency distribution, plotted separately for different types of systems: radio (rotation-powered) pulsars (from the ATNF Pulsar Catalogue, as of June 2007), accretion-powered millisecond pulsars, and burst oscillation sources. The overwhelming majority of rotation-powered pulsars spin slowly; the bar at 0–50 Hz is cut off by the *y*-axis range and includes 1480 sources. The distribution for the accreting sources is much flatter, and is not affected by any known selection effects which make detection of more rapidly-spinning systems less likely.

DISCUSSION

Having presented in some detail the phenomenology of measuring accreting neutron-star spins, I turn to the prospects for the future potential for stringent constraints on the neutron-star equation of state. The combined spin frequency distribution for the 22 burst oscillation sources and millisecond pulsars is approximately flat between 45–620 Hz (Fig. 3). The spin distribution for rotation-powered pulsars, in contrast, is subject to significant selection effects which mask the true distribution. Radio pulsars are subject to pulse smearing due to dispersion in the interstellar medium, which makes previously unknown examples harder to detect. This problem becomes worse for very fast pulsars, and the increasing effect of eclipses by the outflowing pulsar wind further decreases the sensitivity for detection. X-ray pulsations, on the other hand, are not subject to either effect, and thanks to *RXTE*'s timing capability well above 1 kHz, the sensitivity to X-ray pulsars rotating at frequencies well above the current maximum is effectively flat. Thus, accretion-powered pulsars may offer the best chance to detect maximally-rotating neutron stars, and thus provide future constraints on the neutron star EOS.

In the absence of any known selection effects, the present lack of accretion-powered neutron stars spinning faster than 620 Hz strongly suggests that such systems are rare, if they exist at all. One possible explanation for this lack of faster-spinning objects is the increasing role of gravitational radiation which may prevent further spin-up (e.g. [40]). Regardless of the mechanism which apparently prevents further spin-up, this paucity of more rapidly spinning systems has serious implications for the prospects for future detections and corresponding constraints on the neutron star EOS.

To explore these implications further, it is worthwhile to consider how much faster a neutron star need be discovered before significant constraints on the possible EOS are achieved. In this respect the candidate 1122 Hz burst oscillation, even though it has not been confirmed, has prompted a timely exploration of the consequences for the EOS. According to [41], this result leads for the first time to "strong, model-independent observational constraints" to the neutron star EOS (see also [42]). For such a rapidly spinning neutron star to be comprised of nucleonic matter would require a rather large mass of $\gtrsim 2\, M_{\odot}$ (perhaps providing an alternative explanation of why extremely rapidly-spinning neutron stars have been

[3] SAX J1748.9−2021 had previously been reported as a 410 Hz burst oscillation source [39], although that signal was detected only briefly in a single burst, and at low significance. While a source with pulsations and burst oscillations at different frequencies would be truly remarkable, the burst oscillation detection was likely not real.

so hard to find). The rotational mass-radius limit for an 1122 Hz neutron star just intersects the M-R trajectories for several plausible equations of state at the highest possible mass ([1], Figure 2). This suggests that this spin rate is a convenient empirical target for observers; neutron stars spinning slower than this rate likely cannot significantly constrain the EOS (unless other, complementary constraints are available) while neutron stars spinning at even higher rates have a good chance to constrain the EOS.

It is also worth noting that the prospect for access to an X-ray timing mission in the near future is far from guaranteed. The present *RXTE* cycle 12, through February 2009 at the latest, may be the last observing cycle for the instrument[4]. Efforts are underway to continue the mission through 2009 and beyond, but if these efforts are unsuccessful, no alternative timing mission is currently planned for the near future by ESA or NASA. The best chance for a replacement high-sensitivity, high time resolution X-ray instrument is the Large-Area Xenon Proportional Counter (LAXPC) onboard the Indian multiwavelength satellite *ASTROSAT*[5], currently scheduled for launch in December 2009. The LAXPC has comparable spectral and timing resolution to the *RXTE*/PCA, with improved high-energy sensitivity; in addition, the satellite will also feature soft- and hard-X-ray imaging telescopes, an all-sky monitor, and a UV telescope for broadband coverage.

In the unfortunate event that *RXTE* ceases operation before *ASTROSAT* is launched, there will be no further spin measurements for rapidly-rotating accreting neutron stars in the meantime. Even if this situation is avoided, if some phenomenon prevents the spin-up of neutron stars to spin rates much in excess of 750 Hz (as is suggested by the present distribution of measured spins), the prospects for strong constraints on the neutron star EOS by measurement of rapid spins alone appear poor. However, the prospects for constraints via multiple observational measurements remain promising. For the accretion-powered neutron stars, this approach is illustrated by the recent results from EXO 0748$-$676, which combined the spin rate with measurements of the surface gravitational redshift, the peak flux of radius-expansion thermonuclear bursts (the Eddington limit) and the (apparent) blackbody radius of the star from the X-ray flux in the burst tail [43]. Although the spin rate in this system is the slowest measured in any LMXB at 45 Hz, and so cannot alone give any useful constraints on the EOS, the combination of other measurements allowed those authors to rule out all the "soft" equations of state for this system.

[4] URL `http://heasarc.gsfc.nasa.gov/docs/xte/cycle12.html`
[5] URL `http://meghnad.iucaa.ernet.in/~astrosat`

Although this result is not without it's own caveats (see e.g. [44]), many of the issues appear resolvable. The energetics of both thermonuclear bursts and carbon-burning "superbursts" may also allow complementary measurements of the heat flux from the neutron star crust, which also constrains the interior properties and hence the EOS (e.g. [45]).

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TABLE 1. Rapidly-rotating accreting neutron stars

Source	Type*	$\nu_{\rm spin}$ (Hz)	$P_{\rm orb}$ (min)	d (kpc)†	$\dot{M}$ ($10^{-11}\ M_\odot\ {\rm yr}^{-1}$)**	Ref.
			Burst oscillation sources			
EXO 0748−676	BDT	45	229	7.5	20–45 (120)	[22]
4U 1916−05	BD	270	50	8.9	22–110	[46]
IGR J17191−2821	BT	294	...	< 11	...	[23]
4U 1702−429	B	329	1320	5.5	35–80	[47]
4U 1728−34	B	363	...	5.2	45–210	[19]
KS 1731−26	BL	524	...	7.2	85–350	[48]
A 1744−361	BT	530	...	< 9	(< 230)	[49]
MXB 1658−298	BDL	567	427	12	60–200	[50]
4U 1636−536	B	581	228	6.0	55–330	[51]
GRS 1741.9−2853‡	BT	589	...	8	0.01 (1)	[52, 53]
SAX J1750.8−2900	BT	601	...	6.8	20 (180)	[54]
4U 1608−52§	BT	620	773	4.1	100 (530)	
			Accretion-powered millisecond pulsars			
Swift J1756.9−2508	T	182	54.0	8?	> 0.14 (200)	[28]
XTE J0929−314	T	185	43.6	> 4	> 0.4 (30)	[55]
XTE J1807−294	T	191	40.1	> 5	> 0.3 (40)	[56]
XTE J1814−338¶	BT	314	257	< 8	1.4–1.6 (< 60)	[21]
SAX J1808.4−3658¶	BT	401	120.9	3.4–3.6	0.6–1.3 (75)	[25, 26, 32]
XTE J1751-305	T	435	42.4	> 8	> 1.2 (190)	[57]
IGR 00291+5934	T	599	147.4	5–6	1.3 (90)	[58, 29]
			Intermittent pulsars			
HETE J1900.1-2455	BL	377	83.3	5.0	7–70	[34, 35]
SAX J1748.9−2021	BT	442	520	8.1	8 (420)	[37, 38]
Aql X-1¶	BT	550	1137	5.0	105 (510)	[36]

* B = burster, T = transient, L = long-duration ($>$ 1 yr) transient, D = dipping source. Adapted from [8].

† For the sources with radius-expansion bursts, the distance is determined from the mean peak flux of those bursts [17]. For sources with only non-radius expansion bursts, the maximum peak flux of the bursts leads to an upper limit on the distance. For sources with no bursts, the ratio of the long-term average X-ray flux and the expected accretion rate driven by gravitational radiation leads to a lower limit on the distance [29]

** The inferred mass accretion rate, based on the time-averaged broadband X-ray flux and the distance estimate, and assuming a $1.4M_\odot$ neutron star with radius 10 km. For transients, the peak rate observed during outburst is indicated in parentheses. For the long-duration transients, the rate is measured while the source is X-ray active. For sources without bursts, the estimated rate is a lower limit based on the minimum companion mass and the orbital period (following [59]).

‡ The source of the bursts with 589 Hz oscillations assumed by [17].

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¶ Also a burst oscillation source

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